Low-frequency crossover of the fractional power-law conductivity in $SrRuO_3$*

J.S. Dodge,[1,2] C.P. Weber[1], J. Corson[1], J. Orenstein[1], Z.~Schlesinger,[3] J.W. Reiner,[4] M.R. Beasley[4]
[1]Department of Physics, University of California at Berkeley, Berkeley, California 94720 and
Materials Sciences Division, E.O. Lawrence Berkeley National Laboratory, Berkeley, California 94720
[2]Physics Department, Simon Fraser University, Burnaby, Canada, V5A 1S6
[3]Department of Physics, University of California at Santa Cruz, Santa Cruz, California 95064
[4]Edward L.Ginzton Laboratories, Stanford University, Stanford, California 94305

One of the most exciting proposals to emerge from the study of high-T_c superconductors is that Landau's Fermi liquid theory (FLT) breaks down in the metallic state above T_c [1]. This would have profound implications, since FLT provides the foundation for our current understanding of metals, together with systems as diverse as liquid ^{3}He and nuclear matter [2]. Evidence for its breakdown in high-T_c superconductors comes from a variety of experiments, including photoemission, electrical transport, and optics [3]. More recently similar evidence has been found in other compounds [4]. Here we show that the complex optical conductivity $\sigma(\omega, T)$ of one such material, the ferromagnetic metal $SrRuO_3$ [5–8], behaves according to a remarkably simple power-law form, which deviates sharply from the prediction of FLT. This observation provides valuable insight into the nature of charge scattering in unconventional metals.

Infrared reflectivity studies indicate that both high-T_c superconductors and $SrRuO_3$ exhibit conductivity with an anomalous power-law dependence on frequency, $\sigma_1(\omega) \sim \omega^{-\alpha}$, with $\alpha \sim 0.5$ for $SrRuO_3$ [8] and $\alpha \sim 0.7$ in the high-T_c materials [9,10]. The Drude form yields $\sigma_1 \sim \omega^{-2}$ at comparable frequencies. If FLT is valid, the conductivity in excess of Drude must be identified with interband transitions or the incoherent component of the spectrum, and there must be a crossover at lower frequency to the renormalized Drude conductivity [11,12].

Recently, Ioffe and Millis suggested that the entire conductivity spectrum of the high-T_c materials could be understood as a single component, rather than two, as in FLT [13]. The spectrum they derived was generalized by van der Marel [14]. We find that $\sigma(\omega, T)$ of $SrRuO_3$ at low temperature is described well by this equation over nearly three decades in ω (6-2400 cm^{-1}) with $\alpha \sim 0.4$, in strong disagreement with FLT. Our results at frequencies below 100 cm^{-1} were obtained from transmission measurements on thin film samples of $SrRuO_3$ grown epitaxially on $NdGaO_3$ substrates [20,21]. To probe the region where $\omega \sim 1/\tau$, we used conventional Fourier-transform infrared spectroscopy at ALS Beamline 1.4.2 to measure the transmittance (T). For the range $\omega << 1/\tau$, we used time-domain terahertz spectroscopy (TDTHz) to measure the complex transmission amplitude $t(\omega,T)$ in the millimeter wave region of the spectrum. At frequencies above 100 cm^{-1}, we measure the reflectivity from a thick film of $SrRuO_3$ deposited on a $SrTiO_3$ substrate [8]. We have derived $\sigma(\omega, T)$ from each of these measurements.

Using TDTHz spectroscopy, we obtained both the amplitude and the phase of the complex conductivity as a function of temperature and frequency, which we show in Fig. 1 for our most thoroughly studied $SrRuO_3$ film. Also shown are the results of the best fit with $\alpha = 0.4$.

We develop this analysis further in Fig. 2, which shows a logarithmic plot of the conductivity amplitude at our lowest frequency, $\omega 1/2\pi = 0.2$ THz, versus $[\tau(T;\alpha)]^{\alpha}$, with τ in femtoseconds. The plot is parametric in temperature for several different values of α. The best fit to this slope is

*This work appeared in Phys. Rev. Lett. **85**, 4932 (2000).

obtained for $\alpha = 0.4$, and already at $\alpha = 0.6$ a clear deviation is observed. At higher values of α the slope decreases yet further, so the case $\alpha = 1$ corresponding to Drude conductivity requires A to increase strongly with temperature. Thus, $\alpha = 0.4 \pm 0.1$ provides not only the best fit, but also the most compact description of the data.

In Fig. 3 we show $\sigma(\omega, T)$ of $SrRuO_3$ over two and a half decades in frequency, obtained in three separate measurements. Data in the lowest frequency range is taken from TDTHz measurements at the same four representative temperatures shown in Fig. 1, and extends from 6 - 36 cm^{-1}. In the intermediate frequency range 26 - 80 cm^{-1}, we have measured T, which is a real quantity and therefore incapable of providing the complex conductivity without further analysis. The continuity of the results at the crossover frequency of these two distinct measurements may be taken as an indication of the high accuracy with which we have determined the conductivity. At frequencies probed by infrared reflectivity, the conductivity is relatively temperature independent below 100 K, and we show only one measurement taken at 40 K [8].

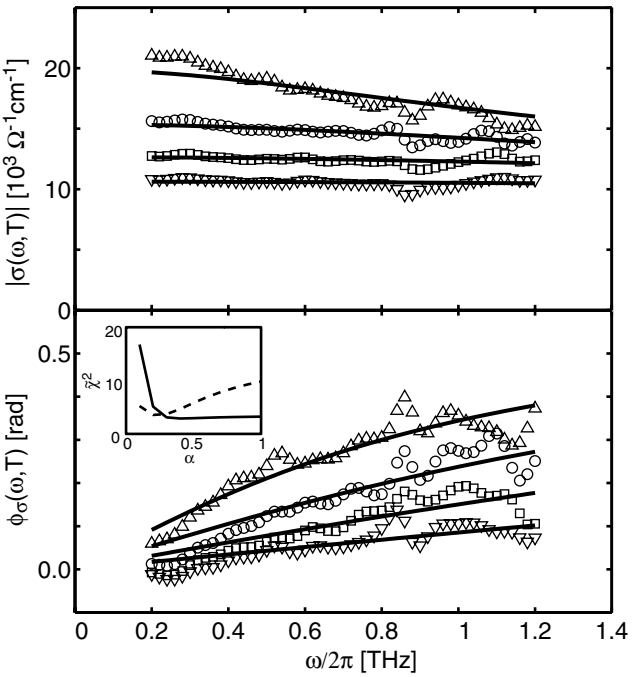

FIG. 1. Measured amplitude (upper panel) and phase (lower panel) of $\sigma(\omega, T)$ in $SrRuO_3$ at four representative temperatures: T = 8 K; 40 K; 60 K; and 80 K. Lines are fits to the data with $\alpha = 0.4$. The inset shows the reduced χ^2 error associated with the phase (solid line) and amplitude (dashed line) fits, as a function of α.

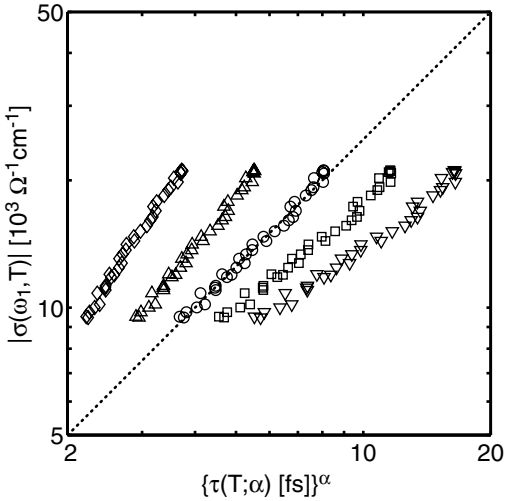

FIG. 2. Logarithmic plot demonstrating the scaling relation-ship of $\sigma(\omega, T)$.

The dotted lines in Fig. 3 show the conductivity calculated using the parameters obtained from TDTHz. With a single global parameter A and a single temperature-dependent parameter $\tau(T)$, this model fits the data exceptionally well, at frequencies 2 orders of magnitude higher than those at which the parameters were obtained. As we increase the temperature above 95 K, both our measurements and earlier reflectivity measurements begin to deviate from the form discussed here, and develop a pseudogap structure which may be related to the transition from ferromagnetism to paramagnetism [8].

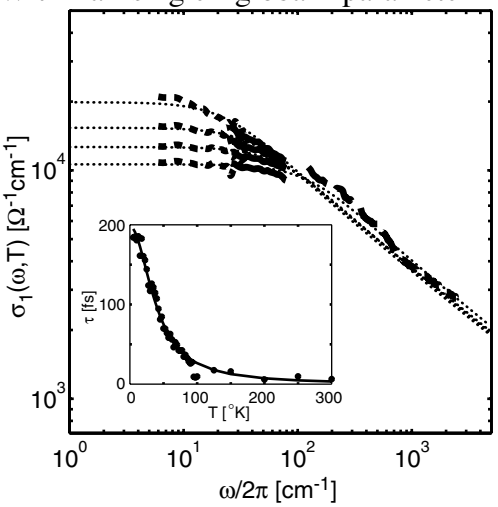

FIG. 3. Logarithmic plot of the conductivity obtained by three methods, in three ranges of frequency. The conductivity obtained from the infrared reflectivity at 40 K is indicated by the long dashed line. Results from far-infrared transmission measurements, as described in the text, are indicated by solid lines, and TDTHz measurements by short dashed lines, with both sets ordered in temperature from top to bottom with T = 8, 40, 60, and 80 K.

As shown in Fig. 3, $1/\tau$ sets the frequency scale at which the $\omega^{-\alpha}$ divergence is cut off, forcing $\sigma_1 \propto \tau^{\alpha}$ in the dc limit. Thus the ubiquitous practice of inferring scattering times from electrical transport via $\sigma_{dc} \sim\tau$ is erroneous whenever the conductivity behaves as Eq. (1) with $\alpha \neq 1$. The resistivity of $SrRuO_3$ for $25 \leq T \leq 120$ K exhibits approximately linear temperature dependence, which then crosses over at lower temperatures to become constant as impurity scattering dominates [7]. In our analysis, this implies a scattering rate with at least a quadratic dependence on temperature.

While evidence for a low-temperature Fermi liquid state in $SrRuO_3$ has been provided by the observation of Shubnikhov–de Haas oscillations, with amplitudes that display the temperature dependence of a Fermi liquid [22], the measurements presented here indicate that this behavior breaks down at much lower energies than would be predicted by conventional FLT. The origin of this fragility, the nature of the low energy scale T_0 which appears to set a crossover scale, and the way such behavior may coexist with the manifestly non-Fermi liquid conductivity form of Eq. (1) remain important open questions raised by these measurements.

In summary, we have studied in detail the complex conductivity of $SrRuO_3$ at low frequencies and temperatures, and shown that it agrees well with a simple phenomenological form. The difference between $\alpha = 0.4$ observed here and the Drude form expected from FLT, with $\alpha = 1$,is reflected in the interpretation of τ, one of the fundamental parameters in the transport theory of metals.

REFERENCES

[1] P. W. Anderson, Science **235**, 1196 (1987).
[2] D. Pines and P. Nozières, *The Theory of Quantum Liquids: Normal Fermi Liquids* (Addison-Wesley, 1989).
[3] J. Orenstein and A. J. Millis, Science **288**, 468 (2000).
[4] M. Imada, A. Fujimori, and Y. Tokura, Rev. Mod. Phys. **70**, 1039 (1998).
[5] I. Bozovic *et al.,* Phys. Rev. Lett. **73**, 1436 (1994).
[6] L. Klein *et al.,* Phys. Rev. Lett. **77**, 2774 (1996).
[7] L. Klein *et al.,* J. Phys. Condens. Matter **8**, 10 111 (1996).
[8] P. Kostic *et al.,* Phys. Rev. Lett. **81**, 2498 (1998).
[9] Z. Schlesinger *et al.,* Phys. Rev. Lett. **65**, 801 (1990).
[10] A. El Azrak *et al.,* Phys. Rev. B **49**, 9846 (1994).
[11] D. B. Tanner and T. Timusk, in *Physical Properties of High Temperature Superconductors III,* edited by D. M. Ginsberg (World Scientific, Singapore, 1992), pp. 363–469.
[12] A. Georges *et al.,* Rev. Mod. Phys. **68**, 13 (1996).
[13] L. B. Ioffe and A. J. Millis, Phys. Rev. B **58**, 11 631 (1998).
[14] D. van der Marel, Phys. Rev. B **60**, R765 (1999).
[15] A. Carrington *et al.,* Phys. Rev. Lett. **69**, 2855 (1992).
[16] R. Hlubina and T. M. Rice, Phys. Rev. B **51**, 9253 (1995).
[17] B. Stojkovic´ and D. Pines, Phys. Rev. Lett. **76**, 811 (1996).
[18] T. Xiang and W. N. Hardy, cond-mat/0001443.
[19] P. W. Anderson, Phys. Rev. B **55**, 11 785 (1997).
[20] C. H. S. Ahn, Ph.D. thesis, Stanford University, 1996.
[21] C. B. Eom *et al.,* Science **258**, 1766 (1992).
[22] A. P. Mackenzie *et al.,* Phys. Rev. B **58**, R13 318 (1998).

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Materials Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, by the Stanford NSF-MRSEC Pro-gram, and by NSF Grants No. DMR-0071949 and No. 9870252.

Principal investigator: J.S. Dodge, Physics Department, Simon Fraser University, Canada. E-mail: jsdodge@sfu.ca